Ultrasonic Attenuation Coefficient of a Hip Prosthesis with Inclusions

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Abstract

In the present work, the ultrasonic attenuation coefficient was determined for a hip prosthesis made of polyethylene and with an internal structure formed by misfitting inclusions. The acoustic energy attenuation throughout the prosthetic stem was estimated by ultrasound excitation of the hip prosthesis and was employed to determine its damping capacity. It was found that while the acoustic wave travels though the internal structure of prosthesis stem, the geometrical arrangement of the inclusions and its particular orientation, provoke scattering of the acoustic, increasing thus the prosthesis damping.

Keywords:

Ultrasonic; Attenuation Coefficient; Hip Prosthesis; Scattering; Inclusions

Introduction

Every year, more than one million one hundred thousand hip prostheses are implanted worldwide, from them it is estimated that 90% of them maintain good functionality for the next ten subsequent years [1]. However, since the artificial joint is used under the same conditions as the natural joint, the former is subjected to larger loads and in consequence to higher friction, wear between the contacting surfaces and the subsequent loosening between the acetabular cup and femoral head. These, in addition to the loosening between the stem and femur and the acetabular cup and hip; are the main causes of failure of the hip prosthesis. This failure will in consequence provoke a second surgery to replace totally the hip prosthesis [2] with the implicit life endangerment.

As described by Seifert [3], the biomechanical reasons for moving and loosening of the acetabular cup and femoral prosthesis are still unclarified. Especially, chronic and mechanical overloads of the interfaces, which are caused by the change of stiffness and damping properties of the whole system, cannot be excluded. To date, the description of dynamic behaviour of hip-joint endoprostheses from the viewpoint of material selection and design is insufficient.

Currently, research continues on development of new designs which could prolong its useful life and reduce the loosening problems in prosthetic elements. An example of the former is the design of hip prosthesis developed at the National Center for Research and Technological Development (CENIDET). This design is a Charnley type prosthesis; made of ultrahigh density polyethylene (UHMWPE) with an internal array of misfitting inclusions. This design was inspired in the bone structure of the femur and mechanical behavior [4].

Among the current technologies to monitor and characterize the material science phenomena, the most popular are acoustic force microscopy, scanning electron microscopy, x-ray diffraction or transmission electron microscopy. If we focus on the human in vivo scale, there are available techniques such as magnetic resonance imaging, computer-assisted tomography or dual energy x-ray absorption. In this work, ultrasound inspection method is employed. Ultrasound is a propagation of elastic waves in solids, liquids and gases with frequencies greater than the upper limit of human hearing (more than 20 kHz) [5], whose characteristics has make him suitable as an inspection tool for non- destructive testing (NDT). In industry the ultrasonic testing is a type of nondestructive testing commonly used to find imperfections in materials and to measure the thickness of objects [2].

Background

Attenuation

When an ultrasonic beam is traveling through an elastic medium; part of the energy is removed by absorption

and scattering. When energy is removed from ultrasound beam, for example an increase in the random movement of molecules, absorption is the phenomena under study [6]; on the other hand, dispersion is considered if part of ultrasound beam changes direction at random. The combination between two phenomena is named as attenuation [7].

From the plane wave propagation equation [8], we obtain the equation to calculate the attenuation of acoustic intensity, such that:

$$A = A_0 e^{-\alpha x} e^{ik(x - V_f t)} \tag{1}$$

Where α is coefficient of acoustic attenuation, k wave number, V_f phase velocity and Ao referenced acoustic amplitude. Acoustic intensity is measured in decibels, so the attenuation coefficient is the amount of decibels per unit length and is given by [5]:

$$\alpha = (20/x) \log (A / Ao) \tag{2}$$

Lamb Waves

These waves are known as dispersion waves or plate waves. The velocity of lamb waves throughout a plate depends of wave frequency and plate thickness. The Scattering depends of wave velocity in frequency. Different wave velocities give different propagation modes, these modes are generated when excitation frequency is varied. These displacements are known as symmetric and antisymmetric modes. There are a finite number of modes and particular acoustic frequency for the plate [9]. A Lamb wave can be generated if the phase velocity of an incident longitudinal wave is equal at phase velocity of particular mode.

Reflection and Transmission of Acustic Waves

The ultrasonic signal is reflected on the boundary where there is a difference in acoustic impedance, for instance: 1) in material discontinuities; 2) by coupling medium used on the test or 3) by a material change which suffer the wave propagation paths when are used composite materials [9]. Acoustic impedance (Z) depends on mass density (ϱ) and propagation path of ultrasonic wave (*C*).

$$Z = \rho\, C \tag{3}$$

Methodology

In this work, ultrasound tests are used to evaluate the behaviour of ultrasonic wave propagation within the internal structure of a hip prosthesis. The internal structure is formed by inclusions as as shown in figure

1. This technique was used to prove the existence of wave dispersion and its related damping. Also this technique was employed to obtain wave attenuation in different measurement points. Due to geometric design and the inclusions arrangement of prosthetic element, only 20 points were selected as measuring point. Figure 2a shows the measurement points proposed. Ultrasonic receiver was placed on 3 different angles: on the top at 0°, on the side at 90° and on the bottom at 180°. Experimental arrangement utilized in order to ultrasound analysis is showed on figure 2.b.

Scan type A [9, 10] was utilized due to equipment characteristics, the ultrasonic emitter was fixed at one end of the prosthesis; and was controlled by a signal generator using a sinusoidal signal of 40kz (nominal frequency). On the other hand, the receiver was fixed in each measurement point. For wave transmission, it was applied a coupling gel between ultrasonic transducers and the surface of the prosthesis in order to increase the acoustic transmission efficiency [9].

Results

In figure 3 are shown the measurements taken for the first four points of the upper part. In figure 3a it is shown the signal acquired for point 1. In this point, the amplitude of the signal (V) can be observed plotted against time (s), in other words, they are plotted in the time domain. The waveform exhibits interferences and maintains average amplitude of 0.03V during the sampling time. It can also be seeing from this figure that the generated signal maintains a relation between wavelength and thickness of the measuring section (λ/h). However, , the propagation path of the ultrasonic wave was not obstructed by any inclusion and no effect is presented on its amplitude or frequency.

A different signal in comparison to the one shown in figure 3a it is shown in figure 3b. Here it is appreciated a periodic wave trend every 0.4 s, with an amplitude around 0.05V. This signal is a characteristic of the fundamental modes from Lamb waves. From the values obtained from the relation λ/h, the presence of symmetric (S_0) and antisymmetric mode of Lamb waves [10] can be calculated. These modes are generated because the propagation path of ultrasonic wave is obstructed in the first inclusion, which produces dispersion when the curvature of inclusion has a particular angle of incidence. In general, the Lamb fundamental modes transport the largest amount of

energy than the modes with higher order. Also the symmetric modes travel faster than antisymmetric. On the other hand, the antisymmetric mode has more amplitude than symmetric [10].

Figure 3c shows a wave shape similar to the signal obtained from point 2. In this, the periodic wave trend has a period about 0.15 s with amplitude of 0.005V. Measurements performed in point 3 shorten the periodicity of the pulses and exhibit dispersion. Also, the modes S_0 y A_0 showed a periodic wave trend with frequency greater than the one experienced in point 2. This phenomenon is originated when the ultrasonic wave travel through more than one inclusion.

Figure 3d shows the periodic wave trend with a period smaller than in the points 2 and 3, but they have the same amplitude. In this signal it can be distinguished the arrival of two fundamentals modes of Lamb waves Similar to that of point 3, the signal showed an increment of periodic wave trains. Therefore, the signal is generated from dispersion caused for all inclusions that obstruct ultrasonic wave. The amplitude signal along the 20 points of measurements were obtained from acquired signals, in figure 3 shows the amplitudes characteristics which were produced by dispersion phenomenon due to the internal array of inclusions in the prosthesis.

From figure 4, the displacements were obtained for upper and lower surfaces, this figure shows the shape of symmetric mode 1 of Lamb waves; the displacement curve is obtained from the lower part where the rotation is 180°, there is dependence of dispersion because it depends on wavelength size, material thickness and inclusions.

After checking the dispersion produced in the propagation of the ultrasonic wave, it is found the ultrasonic attenuation coefficient for each surface considered. Table 1 show the ultrasonic attenuation coefficients which were obtained with the ultrasonic technique. The attenuation curves are shown on figure 5, these results were obtained for 3 different scan positions with ultrasonic receiver. The attenuation in the prosthesis is due to material absorption coefficient and dispersion phenomenon [11].

Conclusions

In this work, the damping of a hip prosthesis with inclusions was evaluated. The ultrasound tests were used to analyze the behaviour propagation of sound wave when it is obstructed by inclusions; it was also used to determine the attenuation coefficient of acoustic energy.

The ultrasonic wave behaviour when it finds an obstacle depends on the obstacle size compare with sound wavelength. If the obstacle size is equal or less than wavelength size of sound wave, the obstacle scatters sound energy on different directions. The attenuation coefficient decreased from 40dB/cm to 12dB/cm where the first inclusions array was found. From this point the decrement is maintain nearly constant to 42. This phenomenon is due the inclination and size of the inclusions with the same slope.

It can observe that the acoustic energy is directed to walls of the prosthesis following the direction of inclusion´s major axis. In this direction is showed the larger stiffness. It can be deduced that the stresses and strains will be affected in the same sense for inclusions with major axis at 0° and perpendicular to the transmission direction as well as the increase of damping and strength. The opposite case occur inclusions with major axis at 90°.

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TABLE 1 ATTENUATION COEFFICIENT OF PROSTHESIS BY ULTRASOUND

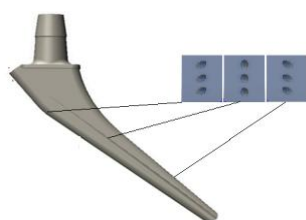| Surface	Measuremented amplitude (Volts)	Distance (cm)	Attenuation coefficient α (dB/cm)
Superior 0°	0.05676275	11	2.98886651
Lateral 90°	0.040457286	13	2.75529733
Inferior 180°	0.04461109	13	2.68999565

FIGURE 1 EXAMPLE DISTRIBUTION OF INCLUSIONS WITHIN THE PROSTHESIS
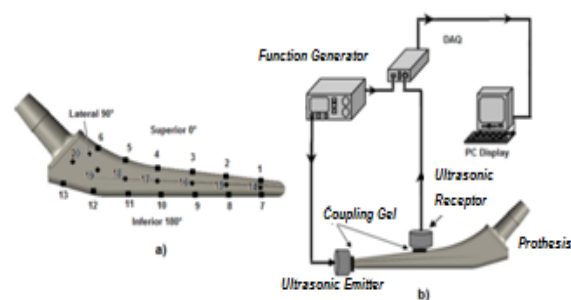

FIGURE 2 POINT DISTRIBUTION FOR ULTRASOUND SCAN AND EXPERIMENTAL ARRANGEMENT FOR ULTRASOUND TEST
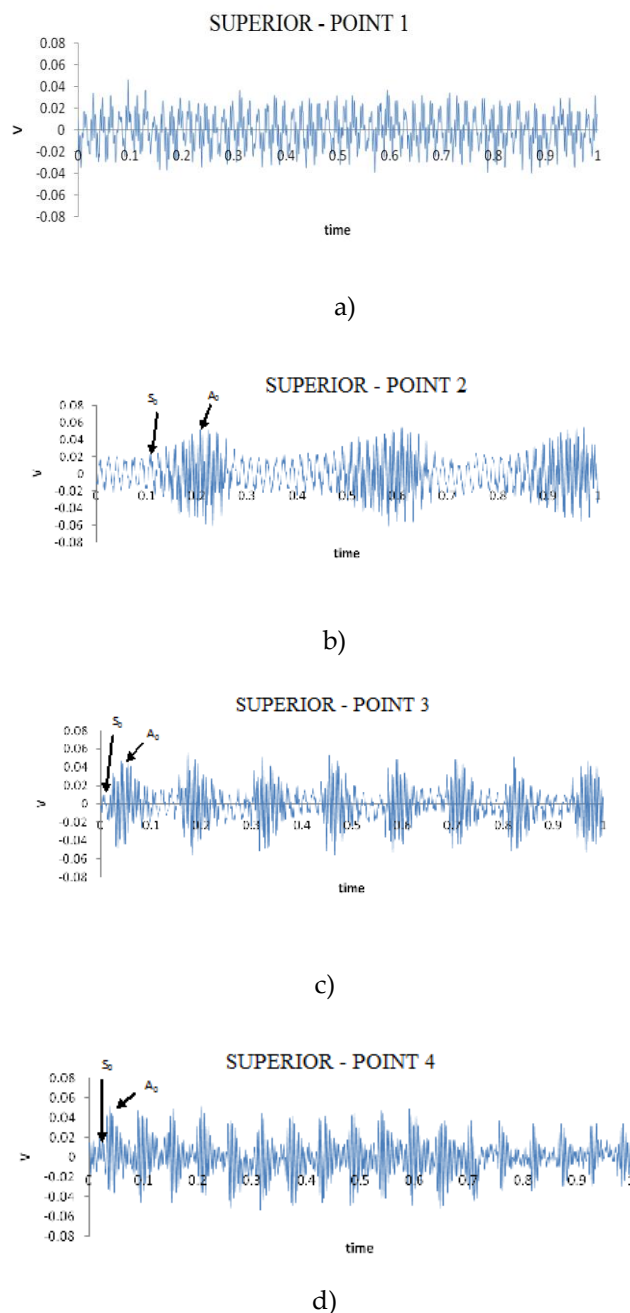

a)

b)

c)

d)

FIGURE 3 SIGNALS OBTAINED FROM MEASURING POITS: a) SIGNAL MEASURED AT POINT 1 AT 0°, b) SIGNAL MEASURED AT POINT 2 AT 0°, c) SIGNAL MEASURED AT POINT 3 AT 0°, d) SIGNAL MEASURED AT POINT 4 AT 0°
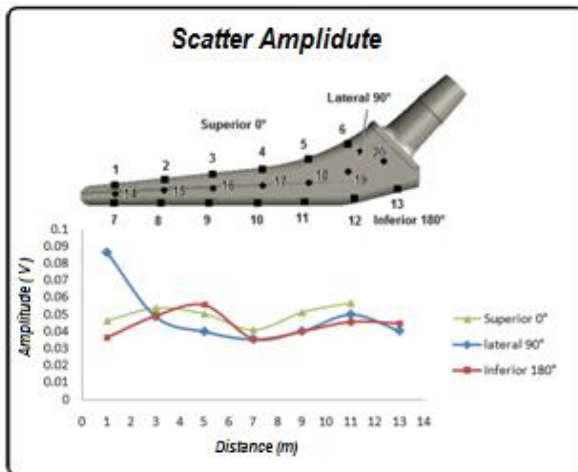
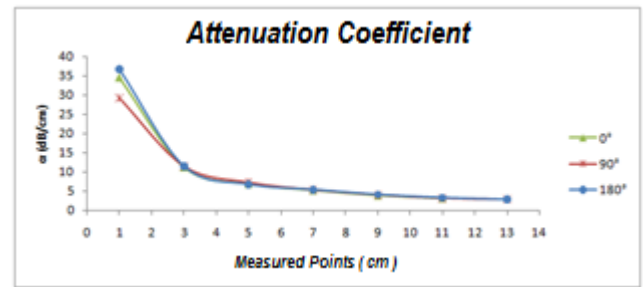FIGURE 4 DISPERSION CAUSED BY PROSTHESIS INCLUSIONS.

FIGURE 5 COMPARISONS OF THE ATTENUATION
COEFFICIENT CURVES IN ORDER TO THREE POSITIONS FROM
RECEIVER